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ABSTRACT

Context. Meridian transit circle observations of the planets and their satellites are regularly performed for ephemerides improvement. Some have been made in Bordeaux observatory during the period 1997-2007.

Aims. This paper presents these observations and makes an analysis of the data in order to determine the accuracy of the observations, their interest for dynamical purpose and a comparison with the dynamical models of the observed objects.

Methods. For the determination of the positions of the planets, the observations of their satellites have been used, providing pseudo observations of the planet. The method is tested.

Results. The results show the interest of continuing this type of observations. Residuals show what ephemerides have to be improved using the present data.

Key words. planetary ephemerides – meridian transit circle – astrometric observations

1. Introduction

Bordeaux observatory continues to perform meridian transit circle observations and has included in its program of observations some solar system objects. Since it appears that more solar system objects observations are needed and that the observations performed with other transit circle instruments are very useful, we wondered if it was worth to continue our observations. The analysis of the reduction and of the comparison of observational data with ephemerides and with other observations made during the same period of time will answer this question.

2. The observations

2.1. The instrument

The Bordeaux meridian transit circle is a 20cm diameter refractor with a 2.37m focal length. The derived scale of the instrument is 87 arcsec/mm. The Bordeaux observatory is located at the following geodetic coordinates: Longitude = 0 deg 31 min 39 sec W, Latitude = 44 deg 50 min 7 sec N and Elevation = 73m. The Bordeaux meridian circle was fully automated from 1984 (Requieme and Mazurier, 1991). It was equipped with a photometric micrometer until 1994 when it received a CCD camera (512x512 pixels) for tests and from 1996 the definitive camera (1024x1024).

A two-stage thermoelectric Peltier unit is used to cool the Thomson 7896M CCD detector below - 40°C in order to limit the resulting dark noise to about 65e-/s. The size of the pixels is 19 μm x 19 μm, corresponding to 1.65 arcsec x 1.65 arcsec in the sky. In declination, the field of the CCD chip is 28 arcmin. In right ascension, the transit time is 112s/cosδ for stars with a declination of δ. This time corresponds to the exposure time of the instrument when used in the drift scan mode.

Drift scan mode was used instead of classical stare mode. The scan mode appeared necessary in view of the characteristics of the transit observations and it allows to observe every night a greater number of stars. Also, the rather long exposure time (about 112s) improves the limiting magnitude up to 16. As stars with a magnitude of 8.5 can be observed without significant pixel saturation, the dynamical range of the CCD unit appears to be about 7.5 mag. The strips observed in scan mode with the CCD detector are narrow in declination (28 arcmin)

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and can be much wider in right ascension, up to several hours. Oppositely, the scan mode presents some drawbacks, as the distortion of star images which can reach a critical level at high declinations. Stars are rejected when their images present an elongation in right ascension six times higher than in declination. As a result, no observation can be done for declinations above 78 degrees. This is not a real problem for the observation of solar system objects orbiting near the equator.

Both GG495 and BG38 filters are used to select a reduced bandwidth of 5200-6800 Å, with a central wavelength of 6050 Å, so as to limit the chromatic refraction to about 0.04 arcsec tanz. Today, the Bordeaux observatory meridian circle remains one of the last instruments of this type in regular operation with the FASTT in Flagstaff (Stone, 1996), the CMASF in San Fernando, Argentina (Muinos et al. 2006) and the Valinhos meridian circle in Brazil (Viateau et al. 1999). For more detailed information about the Bordeaux meridian circle, refer to Viateau et al. (1996).

2.2. The program of observations

The regular observations of solar system objects as Uranus and Neptune have begun in 1982 with a photoelectric micrometer (Rapaport et al. 1987). In 1996, with the automated CCD camera, we have continued this program in observing new objects as Pluto and the main satellites of Uranus as Ariel, Umbriel, Titania and Oberon, as well as Triton, the satellite of Neptune. Moreover, some of the major satellites of Saturn: Titan, Hyperion and Iapetus were observed from 1998. The planet Saturn was not observed, because of its too high brightness. Also, the image processing appeared not to be efficient enough to derive an accurate position of the planet Saturn from its irregular shape, due to the vicinity of the rings. Some results of the first observations of Pluto and Saturn′s satellites were obtained by Rapaport et al. (2002).

Further the regular observations of planets and satellites, the Bordeaux meridian circle is currently involved in several other observing programs. In the recent years, the main of these programs was *Meridien 2000*, planning a systematic observation of the Bordeaux zone of the Astrographic Catalogue ($11\,\mathrm{deg} \leq \delta \leq 18\,\mathrm{deg}$) for more than 3 years. A very consistent catalogue of positions and proper motions of all stars up to magnitude 15 has been derived (Rapaport et al., 2001; Ducourant et al., 2006; Rapaport et al., 2006). Other observing programs concern the asteroids, either to improve their masses (Viateau and Rapaport, 1996) or the accuracy of the prediction of star occultations from *last minute* observations. More recently, another program involving some extragalactic radiosources as blazars, was developed in order to contribute to improve the ICRF system (Charlot and Le Campion, 2004).

3. The reduction

3.1. Image processing

The first step of the image processing is the extraction of the sky background. Two methods may be used. The first one consists in fitting the background to a polynomial of degree from 0 to 3. This is a fast method but it can only be used for moderate gradients. In the case of planetary satellites, located in fields with stronger gradients, the median filter method is preferred. This method consists in searching the median value M of a square of 15 x 15 pixels centered on each pixel and to subtract M to the value of the central pixel.

After the extraction of sky background, the identification of objects is processed from the comparison of each pixel to the standard deviation σ of the residuals of the pixels for each column. An object is identified when 2 consecutive pixels present residuals greater than 3 σ. Two objects can be separated if their distance is greater than 5 arcsec. Then, the photo centre of the images is computed from a two-dimensional Gaussian fit. Bright objects with magnitudes lower than 8.5, as some of the solar system objects involved in our observing program, present images with pixels which may be saturated. Then, such saturated pixels are rejected in the Gaussian fit, so as to limit possible consequent bias in the determination of the photo centre.

3.2. Astrometric reduction

For each star of each individual strip observed each night, the following system of equations below is used to rely the catalogued right ascension α_R, declination δ_R, and magnitude V_R of reference stars to their rectangular measured coordinates (x, y) expressed in pixels and to the measured flux Φ in encoder step units so as:

$$\alpha_R = \alpha_0 + a_1\,\mathrm{x} + a_2\,(\mathrm{y} - y_0)$$
$$\delta_R = \delta_0 + b_1\,(\mathrm{y} - y_0) + b_2\,\mathrm{x} + b_3\,\Phi$$
$$V_R = V_0\;\; 2.5 \log \Phi + \mathrm{cx}$$

α_R and δ_R are the catalogued positions of stars, reduced to the epoch of observation from their proper motions. α_0 represents the local sidereal time at the instant of the beginning of the strip, and δ_0 the declination of the centre of the strip y_0. The flux term in declination $b_3\,\Phi$ is used to recover the excessive shift of charge in the CCD for the images of bright objects. As this effect appears to be negligible in right ascension, no flux term is used in this coordinate. The constants a_1, a_2, b_1, b_2, b_3, V_0 and c, in equations above, are determined by the least-squares method, as well as α_0 and δ_0, also adjusted to observations. Then, the constants are used to determine the new positions and magnitude of the reference stars and of the other non-catalogued objects as secondary stars, planets and satellites. A preliminary catalogue is obtained from the mean positions of all the stars common to the different strips, including secondary stars. The positions of this preliminary catalogue are reintroduced in equations above for a second astrometric reduction. The convergence of the constants generally occurs after 5 successive iterations of this procedure. In order to limit atmospheric effects which can affect the observed positions, a curve is fitted on the residuals of each night of observations by the B-spline method (Viateau et al.1999). The used reference catalogue is Tycho 2 providing data with an accuracy better than 60 mas for positions and 2.5 mas/year for proper motions (Hog et al.2000). So, the positions of solar system objects observed by the Bordeaux meridian circle have a mean accuracy of about

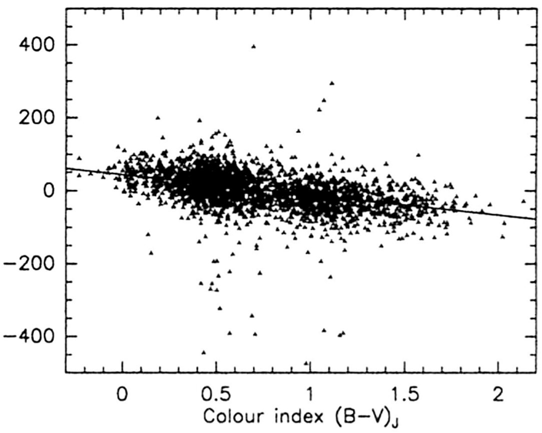

Fig. 1. Chromatic departure in declination vs (B-V) index, expressed in mas (δ between 11 and 18 degrees).

60 mas. They are topocentric and given in the ICRF system and no chromatic correction has been made.

We made several attempts to evaluate the chromatic effects. The first one was derived from the previous work (Rapaport et al.2001) made in the range of declination between 11 and 18 degrees of the M2000 catalog. Fig. 1 visualizes the derived chromatic departure versus (B-V) index. For this range of declination, Fig. 1 shows that chromatic departure is unsignificant, as always under 20 mas, for objects with (B-V) index between 0.5 and 1, as most of solar system objects. In the recent years, Saturn′s satellites were located at a declination close to the M2000 zone. So, their positions presented in this paper must be unsignificantly affected by chromatic effect and do not need any correction. But Uranus, Neptune and Pluto were located at a negative declination from -10 degrees to -15 degrees during the recent period of observations. As chromatic effect is increasing with the zenital distance, the positions of these objects and their satellites can be affected with an higher departure. Due to their low (B-V) index, we have shown, by extrapolating the curve given in Fig. 1 to lower declinations, that the planets Uranus and Neptune remain only affected with very slight chromatic effect under 20 mas. Only their satellites Titania, Oberon and Triton, as well as the dwarf planet Pluto, due to their higher (B-V) index, can be affected with a significant higher chromatic effect which remains lower than positional errors. A second recent evaluation of chromatic effect involving much more stars, including low declination ones, has shown that this effect should be lower than 10 mas, whatever the declination and the (B-V) index of solar system objects. This last evaluation, obtained from real observations, appears to be more realistic than the first one which was derived from an extrapolation of observational effects. Finally, no chromatic correction has been made. Anyway, this point still remains under consideration for the future.

4. The data obtained

The observations were carried out through the program of observations of the Bordeaux transit circle. Planets and their satellites were included in the program when possible. We did not include all the objects for several reasons. For some planets, it was unnecessary to make such observations because of the large sets of modern data (radar or from space probes) available, sufficient for dynamics purpose (Mercury, Venus, Mars). For some planets such as Jupiter and Saturn, and some satellites, such as the Galilean satellites, the magnitude did not allow the observation. Anyway, the accuracy of the transit circle observations of the planets Jupiter and Saturn themselves will not be sufficient for dynamics purpose. We were not able to observe the Galilean, but we observed the Saturnian satellites. The good results obtained will lead us to solve the technical problems in order to observe the Galilean satellites. We will see further that the positions of the satellites may be used in order to propose pseudo-observed positions of their primary that is very useful for Saturn: we observe a satellite, then we calculate the theoretical positions of the center of mass of the system and get a pseudo-positions of the planet. The error on such a position is the one of the dynamical model of the satellite which is much smaller than the error on the measurement of the position of the center of mass of the planet itself. We provide in Table 1, the main characteristics of the observed objects, in Table 2, the number of observations made, and in Table 3 the *rms* of each series of data calculated as follows:

$$rms = \sqrt{\frac{\Sigma(r - rm)^2}{(N - 1)}} \tag{1}$$

where r is the O-C on one observation and rm the mean (O-C) for the series. N is the number of observations. The used ephemerides are DE405 for the planets, TASS for the Saturnian satellites (Vienne and Duriez, 1995; Duriez and Vienne, 1997), LA06 by Lainey and Arlot (2007) for the Uranian satellites and Jacobson (1991) for Triton. It is clear that the quality of the observations depends on the magnitude of the object as shown in Fig. 2. For magnitude larger than 14, the accuracy decreases rapidly as it is obvious in Table 3 for Hyperion and the Uranian satellites. Note that differences appear in right ascension and declination. These differences did not come from chromatic effects but confirm only that a meridian transit circle is more accurate in right ascension than in declination.

All the observational data have been published extensively in the Note Scientifique et Technique de l′IMCCE n° S089 (Dourneau et al. 2007). They are available at the Web address: http://www.imcce.fr/page.php?nav=fr/publications/nst

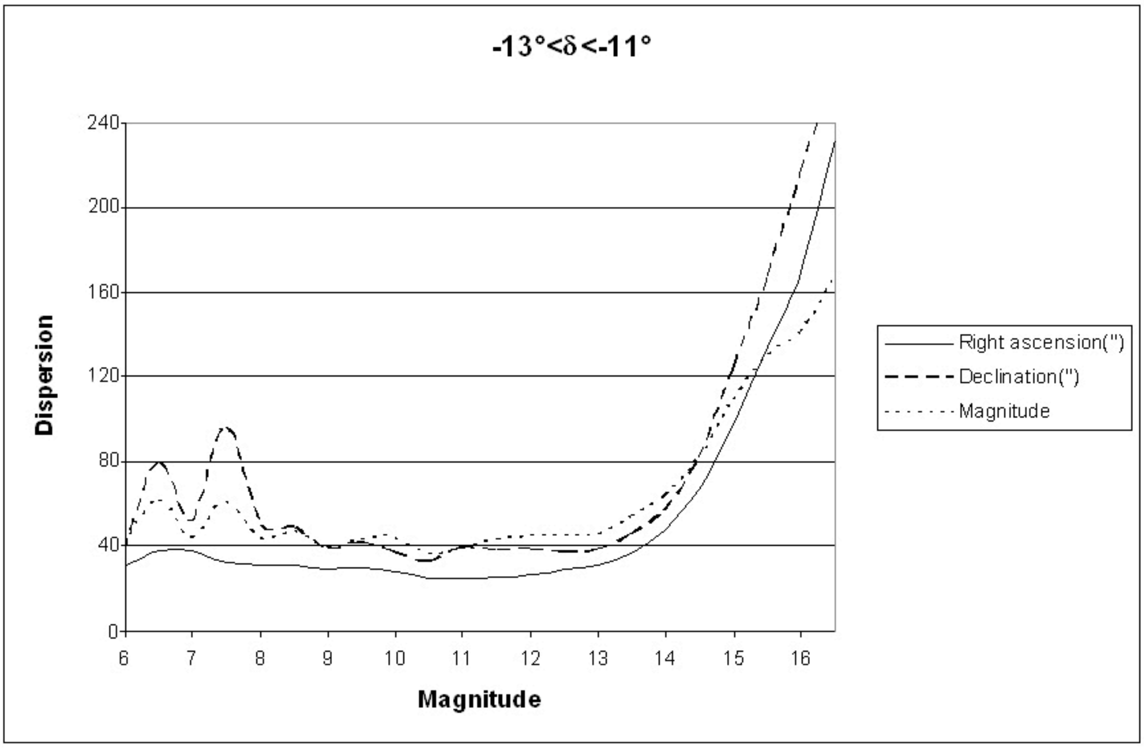

Fig. 2. Dispersion of the residuals (in mas) as a function of the V-magnitude.

Table 1. Main characteristics of the observed objects

Object	mag at opp.	radius km	radius arcsec	phase angle degrees	phase defect mas	orbital period days	max elong arcsec
Titan	8.3	2440	0.35	6	13.8	15.9	209
Hyperion	14.2	200	0.03	6	1.3	21.3	254
Iapetus	11.9	720	0.10	6	3.5	79.3	610
Uranus	5.5	24500	1.75	3	34.4	-	-
Ariel	14.4	580	0.04	3	8.1	2.5	15
Umbriel	15.3	585	0.04	3	8.1	4.1	21
Titania	13.9	800	0.06	3	12.3	8.7	35
Oberon	14.2	760	0.05	3	11.8	13.5	47
Neptune	7.8	25100	1.15	2	15.0	-	-
Triton	13.7	1350	0.06	2	0.8	5.9	17
Pluto	15.0	1200	0.05	2	0.7	-	-

Table 2. Number of observations

Object	1997	1998	1999	2000	2001	2002	2003	2004-05	2006	2007	all
Titan	-	-	14	-	13	-	4	7	12	12	62
Hyperion	-	-	15	-	11	-	7	8	18	11	70
Iapetus	-	-	15	-	16	-	9	9	21	14	84
Uranus	18	10	2	-	50	9	26	22	28	-	165
Ariel	-	-	-	-	-	-	2	-	-	-	2
Umbriel	2	2	-	-	1	-	6	2	7	-	20
Titania	14	5	1	-	29	5	14	12	16	-	96
Oberon	13	6	1	-	38	9	20	12	18	-	117
Neptune	-	-	4	-	-	-	50	19	29	-	102
Triton	-	-	3	-	-	-	48	18	26	-	95
Pluto	-	-	-	-	-	23	-	-	33	-	56

Table 3. Rms of the residuals for each series of data in mas

Object	1997		1998		1999		2000		2001		2002		2003		2004-05		2006		2007		all	
	α	δ	α	δ	α	δ	α	δ	α	δ	α	δ	α	δ	α	δ	α	δ	α	δ	α	δ
Titan	-	-	-	-	58	99	-	-	41	101	-	-	58	88	39	121	78	78	53	125	79	106
Hyperion	-	-	-	-	175	252	-	-	217	344	-	-	257	188	249	360	173	282	219	302	219	302
Iapetus	-	-	-	-	55	61	-	-	76	78	-	-	53	64	34	95	54	54	66	85	92	78
Uranus	41	87	94	92	15	251	-	-	64	114	85	93	66	135	81	142	83	251	-	-	71	156
Ariel	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Umbriel	237	155	100	509	-	-	-	-	-	-	-	-	174	210	5	129	320	251	-	-	229	250
Titania	144	148	84	48	-	-	-	-	217	223	158	115	115	250	104	165	118	135	-	-	155	196
Oberon	153	94	102	174	-	-	-	-	262	231	113	317	237	269	128	240	227	276	-	-	214	253
Neptune	-	-	-	-	50	91	-	-	-	-	-	-	61	77	87	86	93	128	-	-	86	114
Triton	-	-	-	-	105	236	-	-	-	-	-	-	122	233	261	308	321	254	-	-	219	251
Pluto	-	-	-	-	-	-	-	-	-	-	86	209	-	-	-	-	111	137	-	-	103	178

Table 4. Mean residuals (O-C) in α and δ in mas

Object	1997		1998		1999		2000		2001		2002		2003		2004-05		2006		2007		all	
	α	δ	α	δ	α	δ	α	δ	α	δ	α	δ	α	δ	α	δ	α	δ	α	δ	α	δ
Titan	-	-	-	-	3	-7	-	-	95	-2	-	-	136	-37	79	-11	99	-77	174	-86	91	-37
Hyperion	-	-	-	-	-70	-14	-	-	-22	171	-	-	46	310	238	-9	126	-79	146	15	69	36
Iapetus	-	-	-	-	-54	-90	-	-	38	-88	-	-	110	23	94	-72	92	-68	171	-103	71	-72
Uranus	-96	-63	-108	-128	-78	69	-	-	-104	-123	-76	-179	-81	-87	-129	-226	-102	-144	-	-	-101	-129
Ariel	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Umbriel	53	94	-89	208	-	-	-	-	-	-	-	-	-230	-142	-30	93	-100	-80	-	-	-121	-40
Titania	-128	-51	-78	-97	-	-	-	-	-124	-105	-67	-228	-84	-152	-155	-271	-133	-185	-	-	-120	-141
Oberon	-125	-18	-122	-73	-	-	-	-	-186	-69	-77	-318	-198	-143	-160	-281	-109	-218	-	-	-154	-142
Neptune	-	-	-	-	-97	-127	-	-	-	-	-	-	-15	-164	-37	-112	-30	-125	-	-	-28	-122
Triton	-	-	-	-	-75	-216	-	-	-	-	-	-	-4	-212	14	-181	-32	-237	-	-	-10	-213
Pluto	-	-	-	-	-	-	-	-	-	-	-62	-42	-	-	-	-	-21	-158	-	-	-38	-110

5. Comparison of the observations with the ephemerides

We calculated the (O-C) between the observations and the ephemerides in order to see the interest of the observations for the improvement of the dynamics of the observed objects. The figures show the (O-C). Figs. 4 and 6 show the (O-C) in right ascension and declination depending on time and Figs. 5 and 7 the (O-C) of all the observations. Note that the ephemerides are DE405 for the planets, TASS or Do93 by Dourneau (1993) for the Saturnian satellites and LJ86 (Laskar and Jacobson 1987) or LA06 for the Uranian satellites (Arlot et al. 2007).

Table 4 gives the values of the mean (O-C)s for each object and for each opposition. We have to notice that the motions of the planets are slow enough to have a very small variation of the (O-C) over one opposition (a few months) that is not true for the satellites which have a fast motion and then, a variation of the (O-C)s with time over the same period. However, the mean (O-C) for the satellite over one opposition should be very close to the mean (O-C) for the planet. For the Saturnian system, only three satellites were observed showing similar (O-C)s which should correspond to the one of the planet. Hyperion, the magnitude of which is 14.2, has a worse accuracy due to a bad S/N ratio. For the Uranian system, we find the same status. Contrarily to the Saturnian system, the planet itself has been observed that confirms that the satellites show similar (O-C) than the planet. Ariel should be excluded because its poor observation history and Umbriel because the bad astrometric results as consequence of its magnitude. For the Neptunian system, Triton′s (O-C)s discrepancy is larger than the one of Neptune and we do not find similar values. For Pluto, systematic negative (O-C)s seem to appear, as well as for Uranus and Neptune.

In conclusion, assuming that the objects have a magnitude brighter than 15, the observations have an accuracy making them useful for dynamical purpose.

6. Positions of planets derived from observed positions of satellites

The accuracy of the observations of some bright satellites of the planets and the fact that their (O-C)s are mainly coming from the position of the planet, may allow us to make pseudo-observations of the planets through the observation of their satellites. The dynamical models of the motion of the satellites may allow this, since the satellites are orbiting around the centre of mass of the system planet-satellites which is of interest. Note that the direct observation of the planet provides a position of an unknown point, needing a model to go to this centre of mass. The question is: what theoretical model should be the best for that purpose? Fig. 4 shows the (O-C) of the planet Saturn deduced from the observations of Titan, and Fig. 5, the (O-C)s in right ascension versus declination for all the observations. It appears clearly that the ephemerides DE405 of Saturn shows a systematic offset. Fig. 5 a shows the (O-C)s when using the TASS ephemeris for Titan, Fig. 5b when using Do93 Dourneau ephemeris for Titan. The offset to DE405 is quite similar, showing the weak impact of the theoretical model of the motion of the satellite on the making of the pseudo observations of the planet. Contrarily, the impact of the chosen satellite used for the making of the pseudo observation of the planet is very large. Fig. 5c shows what happens when using Hyperion instead of Titan. The discrepancy is very large and the observation of Saturn deduced from the one of Hyperion badly accurate. This was obvious when looking at Table 3: the rms of the residuals reach 0.22/0.30 arcsec for Hyperion and 0.08/0.11 for Titan for all the series of data. In the case of Iapetus, the accuracy of the measurement seems to be better than for Hyperion but the theoretical model is worse than the one of Titan that encourages us to use Titan for determining pseudo-positions of the planet at the present time.

Table 5. Mean residuals (O-C) in α and δ in mas for the period 1997-2005

Object	Bordeaux		Flagstaff	
	α	δ	α	δ
Uranus	-120	-130	-10	-20
Umbriel	-120	-40	-	-
Titania	-120	-140	-100	-80
Oberon	-150	-140	-130	-100

Table 6. Mean residuals (O-C) in α and δ in mas for the 1998 opposition

Object	Bordeaux		Flagstaff		Itajuba	
	α	δ	α	δ	α	δ
Uranus	-110	-130	-160	+40	-330	-10
Ariel	-	-	-	-	-140	+40
Umbriel	-90	+210	-	-	-160	+50
Titania	-80	-100	-140	-20	-130	+90
Oberon	-120	-70	-140	-70	-150	+50

7. Comparison of the observations with other sets of data made at the same time - comparison of the (O-C)s from DE403 and DE405

Since similar series of observations are made in other observatories, it is interesting to compare the results obtained. From 1997 to 2005, observations were performed at Flagstaff using FASTT transit circle facilities. Since Uranus is moving slowly, we may compare the (O-C)s issued from Flagstaff and Bordeaux. Table 5 provides the mean (O-C)s calculated using the LJ86 ephemeris for the satellites and DE 405 for the planet. For Titania and Oberon, both series of observations are in agreement, but for the planet Uranus, the results disagree. It is puzzling that the observations from Bordeaux for Uranus are in agreement with the observations of the satellites, and that is not the case for Flagstaff. Table 6 provides a comparison of the (O-C)s obtained for the opposition of 1998, with also, observations made at Itajuba, Brazil, with a classical CCD target on a 1.6m-telescope (Veiga and Vieira-Martins 1999). The results are much more in agreement except for Uranus itself, probably because of the brightness of the planet which decreases the observational accuracy.

Table 7. Comparison of DE403 and DE405 ephemerides derived from mean residuals (O-C) in α and in δ of Bordeaux meridian circle 1997-2006 observations (in mas unit)

Object	Period	N	Mean residuals (O-C) DE403		DE405	
			α	δ	α	δ
Titan	1999-2006	50	111	-47	71	-26
Hyperion	1999-2006	59	89	20	54	40
Iapetus	1999-2006	70	84	-86	51	-66
Uranus	1997-2005	165	-70	-113	-101	-129
Ariel	1998-2003	2	-1775	561	-1797	546
Umbriel	1997-2005	20	-88	-22	-125	-39
Titania	1997-2005	96	-92	-138	-122	-154
Oberon	1997-2005	113	-108	-134	-138	-150
Neptune	1999-2005	102	-13	-128	-26	-142
Triton	1999-2005	89	-26	-156	-40	-170
Pluto	2002-2005	54	170	40	-39	-91

Mean residuals in Table 7 are displayed in Fig. 3 visualizing residuals in declination versus residuals in right ascension. Fig. 3 shows that the DE405 ephemeris presents no real improvement to the DE403, excepted for Saturn. For the planet Saturn, this result showing the improvement of DE405 with respect to DE403 is in good agreement with Rapaport et al.(2002). For Uranus and Neptune, we confirm the very small discrepancies between both ephemerides, previously mentioned by Rapaport et al.(2002). Fig. 3 shows that such discrepancies are less than 20 mas. We can observe they are rather favourable to DE403 but this is not really significant as we are under the observational accuracy. For Pluto, Fig. 3 also confirms the improvement of DE405 in right ascension and the theoretical difference DE405-DE403 of about 100mas in declination presented by Rapaport et al.(2002). But in this case, we can see in Fig. 3 that this significative difference in Pluto declination does not appear to be in favour of DE405. Finally, the most important improvement of DE405 with respect to DE403 is obtained for Saturn. This can be due to the fact that only new accurate observations of Saturn derived from spacecraft data were used in the DE405 in order to improve the DE403 ephemeris.

8. Comparison of the theories of motion of Saturn's satellites.

Table 8 shows that most of the lowest standard errors are derived from TASS theory by Vienne and Duriez (1995) and by Duriez and Vienne (1997). However, the lowest absolute mean residuals are generally obtained for the other theories Do93 (Dourneau 1987, 1993) for Titan in right ascension and HT93 (Harper and Taylor 1993; Taylor 1992) for Titan in declination as well as for Iapetus in right ascension.

For Hyperion, TASS theory presents all the lowest mean and standard residuals. This means that TASS has really improved HT93 Taylor′s theory (1992) which had previously improved Do93 Dourneau′s theory (1987). The latest theory appears to need, for this satellite, a real improvement so as to include a series of perturbation terms that have not been introduced in comparison to Taylor and TASS theories.

This analysis shows that TASS theory, presenting most of the lowest standard errors, certainly proposes the best model for representing the real orbits of Saturnian satellites. However, this theory appears to need an improvement so as a new fit to observations in order to reduce the significant shift that we have observed in right ascension and in declination.

As a conclusion about the comparison of Saturnian satellites theories, TASS appears to give the best model of orbits as it considers additional terms not included in other theories. But both of the other theories Do93 and HT93 present a better fit to observations than TASS theory for Iapetus in right ascension and for Titan in right ascension and in declination.

9. Conclusion

In conclusion, it appears that transit circle observations are still useful either for the observations of the planetary satellites and for the planets. The pseudo positions of the planets deduced from the observation of the satellites are valuable, mainly for Jupiter and Saturn the centers of mass of which are not easy to measure directly and also for Uranus, increasing the amount of data since Uranus itself is measurable. These observations have an accuracy similar to the one of the direct observations. These observations have allowed us to obtain some results concerning the consistency of planetary and satellite theoretical models. For the planets we have shown that the DE405 ephemeris presents no real improvement to the DE403 ephemeris, except for Saturn. For the satellites of Saturn, the TASS theory has appeared to give the best model of their orbits, but we have shown that the other models Do93 and HT93 can present a better fit to the observations for some satellites such as Titan and Iapetus. So, we encourage the continuation of such regular automatic observations allowing to keep a sample of observations well distributed in time.

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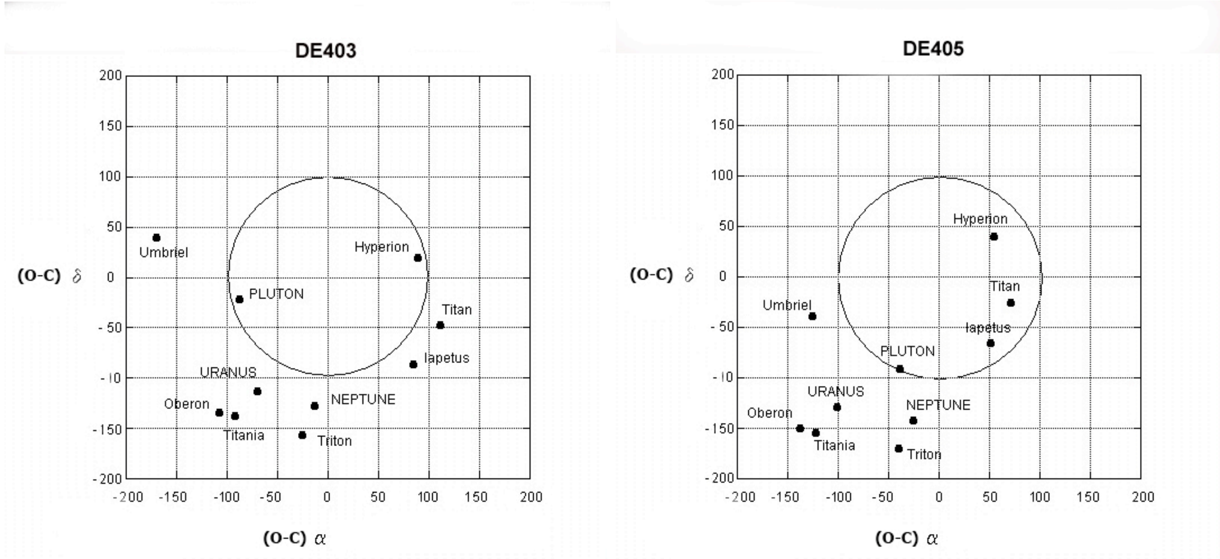

Fig. 3. Comparison of mean residuals (O-C) in mas derived from DE403 and from DE405.

Table 8. Mean residuals (O-C) in α and δ, and standard errors on the residuals (σ_α, σ_δ) in mas of the Saturnian satellites for three available theories. The lower residuals are boldfaced.

Object	Period	N	Theory	(O-C)α	(O-C)δ	σ_α	σ_δ
Titan	1999-2007	62					
			TASS	91	-37	120	111
			Do93	87	-36	126	113
			HT93	89	-35	133	116
Hyperion	1999-2007	70					
			TASS	69	36	228	302
			Do93	523	-114	876	365
			HT93	111	-51	752	356
Iapetus	1999-2007	84					
			TASS	71	-72	115	106
			Do93	32	-81	263	195
			HT93	8	-89	311	133

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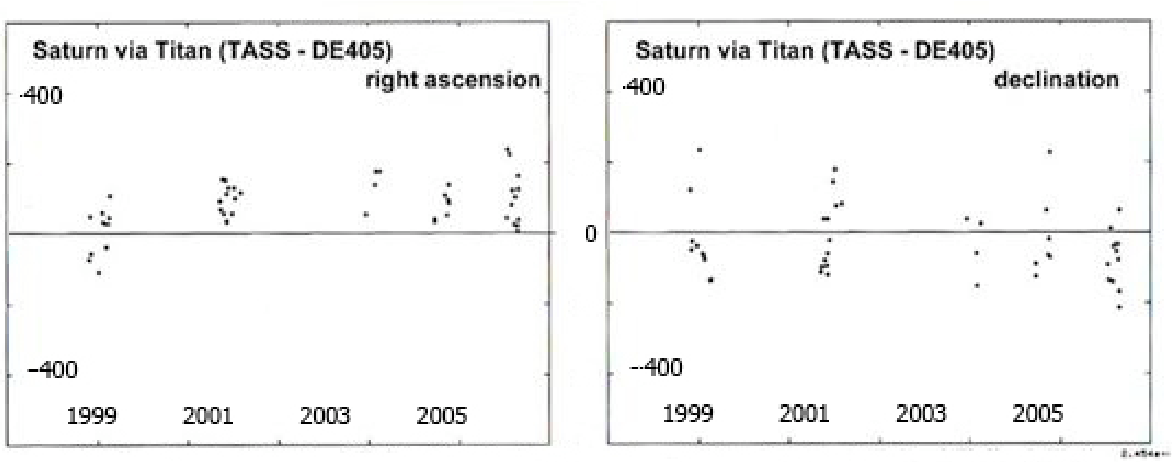

Fig. 4. Residuals (O-C) vs time on the positions of Saturn deduced from the observed positions of Titan.

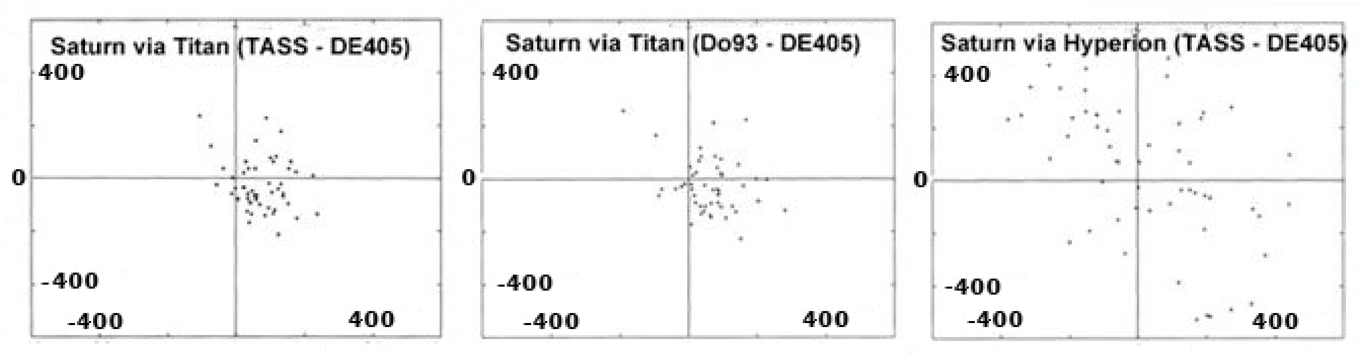

Fig. 5. Residuals (O-C) in α vs δ on the positions of Saturn deduced from the observed positions of the satellites (a: from Titan TASS theory; b: from Titan Do93 theory; c: from Hyperion TASS theory).

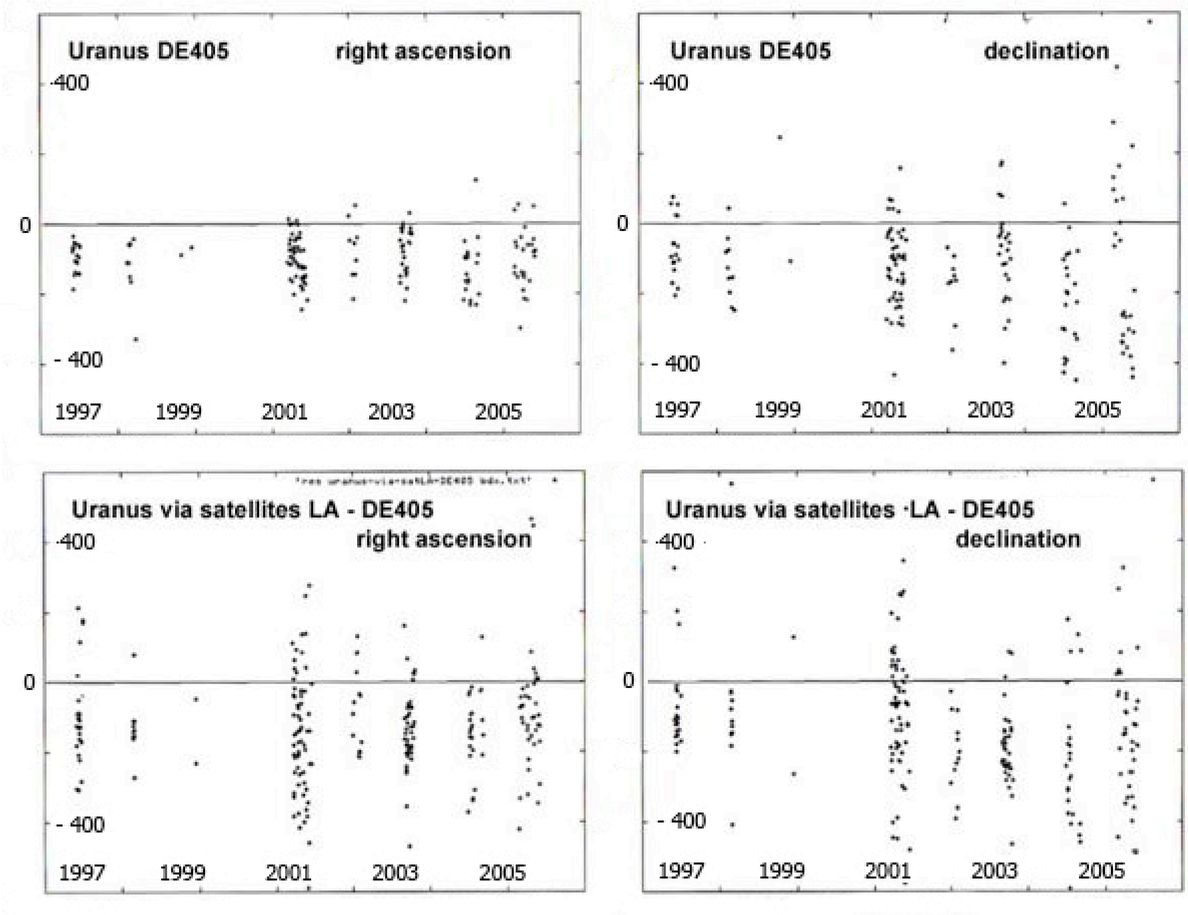

Fig. 6. Residuals (O-C) vs time on the positions of Uranus directly observed and deduced from the observed positions of the satellites.

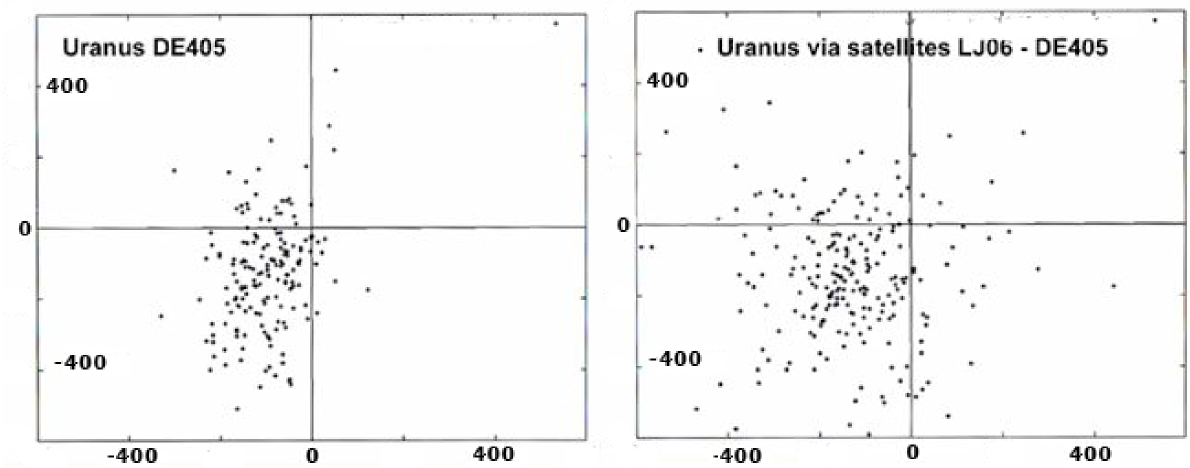

Fig. 7. Residuals (O-C) in α vs δ on the positions of Uranus directly observed and deduced from the observed positions of the satellites.